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# AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 198

# Technical Evaluation Report on the Specialists' Meeting on Aircraft Dynamic Response to Damaged and Repaired Runways

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No 198

# TECHNICAL EVALUATION REPORT

**on the**

**SPECIALISTS' MEETING**

**on**

# AIRCRAFT DYNAMIC RESPONSE TO DAMAGED AND REPAIRED RUNWAYS

by

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- Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;
- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
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## PREFACE

The AGARD/SMP Sub-Committee on "Dynamic Response to Damaged Runways" held technical meetings in Cologne, Germany in 1979, Çeşme, Turkey in 1981 and in Brussels, Belgium in 1982.

Mr Klaus Koenig of VFW has summarized the results of the meetings in this report. His findings, in terms of the general problem, were: damaged and repaired runways are likely to be very uneven and possibly dangerous to aircraft operations; there is very little realistic data on the expected amount and extent of the unevenness. With respect to existing NATO aircraft he found: each aircraft/runway combination must be checked analytically and experimentally; the existing mathematical models for dynamic response of aircraft structures and landing gear are reasonably accurate; some simple modifications to aircraft equipment and pilot technique show substantial improvements in dynamic response. For future aircraft or modifications to the current fleet, there is a need for a NATO-wide "groundworthiness" requirement to allow true *interoperability* of NATO's air forces.

This report completes the task of the AGARD/SMP Sub-Committee on "Dynamic Response to Damaged Runways". However, to improve the prospects for interoperability of NATO's air forces, AGARD/SMP proposes to form a new Working Group on "Landing Gear Design Requirements". The Working Group will consist of experts in structural design, landing gear design and airworthiness from the NATO countries. Their task will be to develop the NATO-wide "groundworthiness" requirements.

JAMES J. OLSEN
Chairman, Sub-Committee
on Dynamic Response to Damaged Runways

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EVALUATION REPORT OF THE AGARD SPECIALISTS MEETING
ON AIRCRAFT DYNAMIC RESPONSE TO DAMAGED AND REPAIRED RUNWAYS
IN BRUSSELS, SPRING 1982
by

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SUMMARY

Methods were presented by which the capability of aircraft to operate on uneven runways can be determined and improved. It was, however, found difficult to establish realistic uneveness data. Nevertheless, it is important and urgent to elaborate and agree on international "ground-worthiness" requirements.

1. GENERAL

This specialists meeting of the AGARD Structures and Materials Panel was prepared by 3 unclassified Pilot Papers presented in Cologne/Germany at the fall meeting 1979 (s. reference 1) and 3 papers given in Cesme/Turkey at the spring meeting 1981. In Brussels/Belgium, 14 papers were presented and about 9o persons attended the meeting which was followed by a round table discussion and a subcommittee 89 session.

The meeting can be regarded as a success. It brought together a large number of undercarriage, dynamic response and runway repair specialists. It was therefore possible to collect a very large amout of information concerning undercarriages and aircraft behaviour on uneven runways. Details from 12 different aircraft were given and facts from another 12 aircraft were mentioned for reference. This information is already published (s. reference 2), this being all the more important as publications on undercarriages were relatively rare in the past.

Yet the main task of this AGARD activity was to help NATO to improve its capability to operate aircraft on damaged and rapidly repaired runways. This aim was approached in three different steps:

Firstly by studying the technical problem, secondly by reviewing operation and improvement procedures for existing aircraft and thirdly by elaborating design requirements for future aircraft.

The study of the technical problem made clear that rapidly repaired runways can be rather uneven and that aircraft can be endangered by this situation. However, no realistic data regarding the dimension and distribution of the uneveness could be obtained. Nevertheless, problem areas at the aircraft were established as well as possible remedies to improve the overroll capability. Sufficiently accurate mathematical models were generally found.

A review of existing aircraft revealed the following: Firstly, it was shown and confirmed that it is necessary to check and determine the overroll capacity of each individual aircraft type which is to be operated on rapidly repaired runways.

Secondly, it was found that some aircraft could be improved considerably by means of minor modifications to the undercarriages.

Thirdly, general and individual handling or operation regulations were established by which the overroll capability of aircraft can be increased. A pilot training was nevertheless found necessary.

Fourthly, it was felt that airport operator and runway repair personnel should be informed of the available aircraft overroll capacity or the required repair quality so that, after the aircraft specialists and the runway specialists have commented on and discussed the matter, a definition of repair standards would be possible. Only then can a MOS strip selection procedure be defined. Finally, if this all is achieved on an international basis, it will also improve interoperability of NATO aircraft. As far as future aircraft are concerned, it was found that the main task will be to elaborate and establish a reasonable "ground-worthiness" requirement. One proposal was already made at the meeting. After discussion and after the already initiated check of this proposal an internationally agreed requirement should be established and proposed to the different national military authorities for inclusion into their individual regulations. A rough summary of the main subjects of all the presented papers is given in tables 1 to 5 of this report but the details are evaluated in the following.

## 2. THE REPAIRED RUNWAY

The topic of all the activities has been "Aircraft Dynamic Response to Damaged and Repaired Runways" which means that the repaired runway has to be studied first. The uneveness of such a repaired runway leads to an excitation of the aircraft.

Papers 6, 7 and 8 (see list of papers and references) of the presented 2o papers reported about different repair methods and paper 1 referred to two other methods. Yet no paper provided real measured data with regard to the uneveness of the repaired surface. Only in paper 9 some hints are given about the scatter of peak height of UK-RRR mat profiles. Therefore, most of the other studies presented used more or less arbitrary definitions of the uneveness to which the aircraft has to respond or tried to find out which uneveness may be overrolled without endangering the aircraft. In papers 14 and 18 deterministic rough profiles were used whereas in most papers (1, 2, 1o, 13, 14, 15, 18 and 2o) single or multiple mats, bumps, spalls or 1-cosine waves with specially defined dimensions were studied. Only in paper 14 the random aspect was mentioned and in papers 1, 1o, 13, and 2o the influence of the spacing of repaired paths was studied. The uneveness mentioned most frequently, especially in the US papers, was that introduced by paper 1 and designated "Repair category A to E".

These facts illustrate the dilemma. No real information is available about the uneveness. It is only known that a rapidly repaired runway is more uneven than the original runway and that a large scatter may exist, especially under realistic wartime conditions.

## 3. COMPUTATION METHODS

4 papers (11, 12, 13 and 14) were concerned with the mathematical modelling of aircraft in relation to the dynamic response problem in question. The information mostly consisted of verbal explanations but paper 14 contained a lot of mathematical equations showing the general assumptions and the solution method.

## 4. RESULTS OF TESTS OR COMPUTATION

13 papers (1, 2, 3, 9, 1o, 11, 12, 13, 14, 15, 18, 19, 2o) presented test and computation results and 7 papers (1, 2, 13, 14, 15, 18, 19) gave a comparison between tests and computations. With few exceptions, these comparisons showed a very good agreement. This fact should indicate that very good computation methods are available nowadays. Nevertheless paper No. 9 and 19 showed from tests that some difficulties are still unsolved. One difficulty concerns the uncertainity or random distribution of some of the values or data to be included in computations (s. paper 9).

Another difficulty concerns the air solution and oil foaming in the shock absorber, when air and oil are not separated by a separator piston, and the heat transfer to and from the air spring of the shock absorber.

A further point mentioned was that the damping law at unsteady small compression or extension speeds as usual for ground roll seems to need some further scientific investigation in order to find the appropriate mathematical formulation.

The best agreement between test and computation was most often found for vertical undercarriage loads and rigid body accelerations of the aircraft. The most sensitive areas seemed to be external stores and their loading, where the agreement was often rather poor. Nevertheless, it became evident that it is possible to compute the loading and behaviour of aircraft moving over uneven ground sufficiently accurately at a reasonable price, even though certain improvements may still be necessary for some parameters.

Finally, it must be mentioned that only one paper (No. 12) studied the question of negligible parameters to gain some computer time and cost reductions.

## 5. PROBLEM AREAS AT AIRCRAFT OR UNDERCARRIAGES

A fact frequently mentioned was that the vertical limit loads of the nose gear were exceeded when the aircraft had to pass an uneven runway (papers 3, 9, 1o, 12, 15, 17, 19, 2o).

The main gear was mentioned less frequently (papers 1, 9, 1o, 19, 2o) and sometimes together with shock absorber (papers 9, 12, 15, 17, 19) or tyre bottoming (papers 1, 3, 17, 2o).

In general, the most critical loads and therefore the loads of greatest relevance to the mass or weight of an undercarriage are the horizontal loads. These are not very much increased by the uneveness of the surface.

Therefore, it is to be expected that for new aircraft designs the necessary changes for improvements will not increase the undercarriage weight very much.

Other problem areas found were:
- wing loading at inner, mid or even outer span (paper 1o, 12)
- *fuselage loading (paper 1o)*
- equipment loading (paper 9, 17)
- cockpit accelerations unbearable for the pilots (paper 2, 9, 12)
- loss of directional stability (discussion of paper 9)
- loads at stores on external pylons (paper 2, 1o, 17, 19)

## 6. PERTINENT PARAMETERS

There are a lot of parameters regarding the aircraft, the undercarriage or other aspects which have a large influence on the capability of an aircraft to pass uneven runways.

The parameters most often mentioned were the rigid body modes heave and pitch. Consequently the weight and the moment of inertia of the aircraft are of major influence. Lighter aircraft should pass the uneveness better.

The elastic modes (s. paper 2, 11, 12, 13, 19) are often negligible, however, not if problems such as external store vibration or wing bending are studied. Under these circumstances it was found very detailed and accurate elastic modes would have to be included into a computation.

Another critical parameter is the aircraft ground roll velocity or acceleration or deceleration. Depending on the type or the dimension of the uneveness there are critical and uncritical velocity ranges (s. paper 1, 9, 13, 15, 18, 19). The aerodynamic loads generally have a large influence after rotation of the aircraft, that is if a real lift force is acting. This force reduces all problems or allows the passing of more uneven runways (s. paper 1, 2, 9, 12, 19). Yet sometimes (s. paper 13, 19) secondary aerodynamic effects such as ground effects, thrust effects or propeller slip stream effects also have some influence on the loading and behaviour of aircraft.

This was not found in all studies so that it can be concluded that special conditions at these types of aircraft may be responsible.

Further parameters having a large influence result from the handling of aircraft. For instance, it was reported that braking (s. paper 9, 12, 13, 17, 19) may result in very dangerous loading of the nose gear and an appropriate elevator operation (paper 9, 12, 13, 19) may reduce the undercarriage loads appreciably. Thrust reverse (paper 9, 17, 19) may also cause some problems like braking but even the thrust run up (s. paper 13, 19) may be noticeable.

The fact that these parameters are of influence must primarily result in an individual handling requirement for each aircraft type, and the pilots must be trained in these special handling procedures. Papers 9 and 19 showed that this fact is important. Moreover, these handling procedures must be included in any computation or theoretical prediction of the aircraft loads on uneven ground. It will also be necessary to include some procedures in design or airworthiness requirements to be established.

It is then also necessary to consider parameters of the undercarriages. The first parameter is the location of the undercarriages at the aircraft. This issue was only considered in paper 2o in connection with the question of the allowable turn-over angle. Nevertheless, a further aspect should be mentioned, that is the effect of mass coupling. This effect is well known from the time when no computers were available, when nose and main undercarriage loads were calculated separately for a so called "unit mass" associated with each individual gear. The mass coupling parameter is defined by $(I/m)/(a \cdot b)$, the ratio of the square of the radius of inertia of the aircraft divided by the distance "a" of the nose gear to the centre of gravity and the distance "b" of the main gear to the centre of gravity. If this parameter is "1", any excentrically acting vertical load of one undercarriage results in rigid body translatory and rotatory movement of and around the centre of gravity which is superimposed in such a way that the resting pole or the centre of rotation is exactly positioned on the connection point of the other undercarriage at the aircraft. This means that a main gear excited by an uneveness of the runway is not able to produce any vertical load increase on the nose gear and vice versa.

Therefore it would appear sensible to consider this mass coupling for new designs or handling recommendations for existing aircraft. A spring coupling between nose and main gear which acts similarly to the mass coupling was mentioned in paper 1 but no detailed study was presented.

It is felt that aircraft of a new generation which are to be designed to more severe ground roll requirements should take advantage of the benefits an appropriate mass and spring coupling may give.

The next undercarriage parameter is the kinematic of the gear. This parameter was mentioned by papers 11 and 2o. In the latter some advantages of the angled lever design were listed but in the end a simple cantilever design was recommended, built and successful. The elasticity of the gear structure (not of the shock absorber or the tyre) is also a parameter mentioned. In the discussion of paper 15 it was said that horizontal elasticity may have a minor influence whereas paper 11 tried to show that the vertical elasticity may be of influence under special conditions, especially if higher frequencies are important for the loads of the aircraft. The mathematical modelling of a multidirectional elasticity was not mentioned in the papers.

Undercarriages with active control were not really mentioned either. This is astonishing because such undercarriages may have a much better overrolling capability. Still, this aspect might be taken up in future.

The main parameters of the shock absorber mentioned (s. paper 1, 2, 9, 15, 17, 19, 2o) were the residual stroke, the air spring stiffness and the limit load. These parameters must be considered together. It was understood that undercarriages designed to the requirements of today are often very good "landing gears" but poor for rolling on more or less uneven runways. Papers 1, 18, and 19 made clear that by a very small increase in the residual travel combined with a reduction in strut stiffness - it is often possible to improve the overroll capability of the undercarriage very considerably. The limit loads may be increased by that measure but the amount is very small and the benefit much larger than the disadvantage.

Consequently, the general recommendations consisted in reducing the air spring stiffness around the point of the static load, increasing the residual travel up to some centimeters (or "better" inches) and allowing a small percentage of higher vertical loads within the shock absorber. Reference should, however, again be made to the fact that especially for undercarriages without separator pistons, a better mathematical modelling may be necessary for the air spring.

Another important parameter mainly mentioned in papers 3, 9, 11, 18, 2o is the damping. The general feeling is that the damping at ground roll and at landing should be different and specially tailored.

As far as the wheels are concerned the question of the number, size and mass arose. For the mass there is no much choice and the question of number and size is related to the size and type of tyre. This question was mentioned mainly in papers 2, 9, 19, 2o. The tyre stiffness is as important as the shock absorber stiffness and this stiffness is influenced by the tyre size and pressure. Yet, for the overroll characteristic at concrete steps or at other obstacles, the size itself is determining. A sufficient "swallow up" capacity of the tyre is necessary.

Regarding parameters not associated with the aircraft or the damaged part of the runway, papers 9 and 12 mentioned the natural wind. Nevertheless the most important of these parameters was found to be the natural uneveness of the undamaged runway. This was reported in papers 2, 9, 12, 14, and 15. It is a fact that the natural uneveness will also excite an aircraft so that statistically the repaired area of the runway is encountered with initial conditions varying from test to test. The influence may be rather large as is clearly shown in paper 15. An evaluation of the overroll capability should therefore take this factor into account. Finally, papers 9 and 19 must be mentioned as these papers gave details on how large the deviation from nominal values may be for some parameters under operational conditions. Mainly concerned are the charging pressure of shock absorber and tyre as well as the amount of uneveness of the repaired runway and the application of brakes, thrust, elevator or others by the pilot.

## 7. TEST FACILITIES

Only two papers (16 and 18) were concerned with lab-test facilities for undercarriages or complete aircraft. As explained by the author of paper 16, it is quite common for land vehicles to be tested extensively under lab conditions. From the discussion ensuing the presentation of this paper, the impression was given that field testing is prefered for aircraft design although, if it were more common to design aircraft for a better ground rolling capability, this opinion may change.

## 8. UNDERCARRIAGE HARDWARE ADAPTATION

Fortunately, two papers (18 and 2o) giving details on the results of hardware changes could already be presented at this meeting. New undercarriages having a better capability for overrolling uneven ground were developed for two existent aircraft so that a smaller dynamic response to damaged and repaired runways was achieved. In both cases one was given the impression that very good results could be reached by only minor and not completely new and unusual modifications to the original undercarriages.

These changes were:
- Increased total shock absorber stroke
- Increased residual stroke
- Reduced air spring stiffness
- Different damping for landing and ground roll
- Tailoring between nose and main gear
- Larger tyres

Naturally, some weight penalties have to be accepted for the improvements but no real reduction in landing capability is necessary.

## 9. RECOMMENDATIONS FOR AIRCRAFT HANDLING

The handling of the aircraft may considerably increase or reduce the capability of an aircraft to overroll uneven ground. Therefore, it is necessary to include the question of handling in all studies and requirements. Examples were given in papers 1, 1o, 13 and 19. In general it is recommendable to:

- start take off on the smoothest part of the MOS
- use only light braking and thrust changes
- use nose up elevator position if nose gear is endangered
- use lighter aircraft weight
- use an aft CG position if nose gear is endangered
- use lowest tyre pressure
- put fuel in centre not in outer tanks
- to touch down on unrepaired original surface
- operate with very low speeds on taxiway
- make no sudden stops or turns or pivoting before encountering repaired patch.

## 1o. DESIGN REQUIREMENTS FOR FUTURE AIRCRAFT

To achieve aircraft with a good capability of overrolling uneven ground it is not sufficient to have the necessary design "know how". An adequate airworthiness or in this case "ground worthiness" requirement must also be available. This must be the same for all NATO countries if interoperability is desired and the requirement should be issued very soon.

Paper 17 and the round table discussion were mainly concerned with that question. There it was made clear that the up-to-date existing national requirements are rather different so that it may be difficult to reach interoperability on such a basis. Furthermore, it was seen that the existing requirements are not sufficient, which is also proven by the fact that aircraft built to these requirements sometimes have a rather poor capability to operate on uneven runways. Therefore a new, internationally agreed definition of runway uneveness is necessary. The definition should be simple. The uneveness does not have to be a real one, but should, under all circumstances, lead to an undercarriage design having a good capability to operate on rapidly repaired runways.

After agreement, the uneveness should be included in each national airworthiness requirement.

In addition, it was proposed to include into STANAGs, concerned with runway repair, some definition of a minimum repair quality to make sure that the aircraft and the runway are compatible and also to ensure that neither the undercarriage designer nor the civil engineer have to put too much effort and costs into their job.

AGARD could perhaps help to reach this aim by compiling a list of the different existing repair methods and assessing the type and level of uneveness to be expected.

The process of definition for a reasonable uneveness was already initiated by the proposal given in paper 17. In the subcommitee meeting which followed the round table discussion, it was decided to study the revised proposal NATO-wide by calculating the dynamic response of all military aircraft for which mathematical models are already available. Results should be discussed at the next meeting to ensure that the final design requirement leads to better undercarriages for smaller and larger aircraft and for different distances between holes (or scabs or spalls) and different repaired patches.

## 11. RECOMMENDATIONS FOR REPAIR QUALITY, MOS SELECTION AND INTEROPERABILITY

If an aircraft is not designed for any realistic "ground-worthiness" it may then only have a limited overroll capability. If, in spite of that, one tries to operate the aircraft on a repaired runway a special repair quality would have to be required. Information about this was given in papers 1, 4, 1o, 13 and 2o. Recommendations for MOS selections were given in paper 4 for the example of one aircraft. These are based on the aircraft capability and the intention to achieve the quickest and cheapest repair.

In paper 5 and 9 some proposals were given to improve NATO's aircraft interoperability in view of the fact that NATO must have the possibility to operate different aircraft built in different countries on different runways distributed throughout the NATO countries.

However, the fact that it will be difficult to reach this aim became very clear at the round table discussion. Finally, it was thought necessary on the one hand, to define some minimum repair qualities and, on the other hand, to exchange some data concerning the various overroll capabilities of modern aircraft to improve their interoperability. Nevertheless, it may prove necessary to accept - as the author of paper 9 proposed - certain levels of risk for operations on damaged and repaired runways.

## LIST OF PAPERS

Papers presented at Cologne (s. ref. 1)

1. Caldwell, L.R., A.G. Gerardi, M.R. Borowski "Runway Surface Roughness"
2. Payne, B.W., A.E. Dudman, B.R. Morris, M. Ormerod, C. Brain, "U.K. Approach to Aircraft Dynamic Response on Damaged and Repaired Runways"
3. Krauss A., O. Bartsch, G. Kempf "Parameters Affecting Aircraft Performance on Runways in bad Condition"

Papers presented at Cesme (s. ref. 2)

4. Strickland W.S., L.R. Caldwell "Minimum Operating Strip Selection Procedure"
5. Caldwell L.R., A.G. Gerardi "Proposed Specifications for International Interoperability on Repaired Bomb-Damaged Runways"
6. Kempf, D. "Damage Control on German Airfields with Particular Regard to Rapid Runway Repair"

Papers presented at Brussels (s. ref. 2)

7. Bergholz "....."
8. A.F. Tovar de Lemos "Application of Semi-Rigid Pavements in Rapid Runway Repair"
9. Brain, C.J. "The Repaired Runway Operational Environment"
10. Holpp, J.E. "Project Have Bounce"
11. Krauss, A., O. Bartsch and G. Kempf "Influence of Mathematical Modelling of Undercarriages on the Prediction of Aircraft Loads due to Damaged and Repaired Runways"
12. Payne,B.W., A.E. Dudman, B.R. Morris, M. Hockenhull "Development of a Cost-Effectiveness Approach to Modelling Aircraft Dynamic Response to Damaged Runways"
13. Gerardi,A.G., L. Minnetyan "Status of Computer Simulations of the F-4, F-16, A-1o, C-13o and C-141 Aircraft and an Alternative Simulation Technique"
14. Petiau,G., A. Celier "Méthodes de Simulation Numérique du Système Avion Atterisseur"
15. Ottens, H.H. "Calculated and Measured Landing Gear Loads for the NF-5 and F-16 Aircraft Taxiing over a Bumpy Runway"
16. Paraino, J. "Laboratory Testing Systems for Structural Dynamic Response to Large Scale Disturbances"
17. Hacklinger, M. "The Problem of Design Criteria for Aircraft Loads due to Rough Runway Operation"
18. Haines, G. "Landing Gear Shock Absorber Development to Improve Aircraft Operating Performance on Rough and Damaged Runways"
19. Crenshaw, B.M. "Roughness Considerations for Transport Aircraft
20. Buttles, R.F., R.D. Renshaw "Fighter Landing Gear for the 8o's"

## REFERENCES


1. AGARD Aircraft Dynamic Response to Damaged Runway. AGARD-R-685 (1979)
2. AGARD Aircraft Dynamic Response to Damaged Runways. AGARD-CP-326 (1982)

TABLE 1 : MAIN SUBJECTS MENTIONED BY THE DIFFERENT AUTHORS

| " A/C Dynamic Response to Damaged and Repaired Runways " | Presented Papers | | | | | | | | | | | | | | | | | | | | RTD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | |
| | Col. | | | Ces. | | | Brussels | | | | | | | | | | | | | | |
| | | | | | | | overv. | | | | math. | | | | te. | | design | | | | |
| Available repair methods | (x) | | | | | X | X | X | | | | | | | | | | | | | |
| Measured uneveness data | | | | | | | | | (x) | | | | | | | | | | | | |
| Computation methods | | | | | | | | | | | X | X | X | X | | | | | | | |
| Results of test or computations s. Table 2 | X | X | X | | | | | | X | X | X | X | X | X | X | | | X | X | X | |
| Problem areas of A/C and U/C s. Table 3 | X | X | X | | | | | | X | X | | X | | | X | | X | | X | X | |
| Pertinent parameters of A/C .. s. Table 4 | X | X | X | | | | | | X | | X | X | X | X | X | | X | X | X | X | |
| Pertinent parameters of U/C s. Table 5 | X | X | X | | | | | | X | | X | X | X | X | X | | X | X | X | X | |
| Test facilities | | | | | | | | | | | | | | | | X | | X | | | |
| U/C hardware adaptation | | | | | | | | | | | | | | | | | | X | | X | |
| Recom. for new A/C design | | | | | | | | | | | | | | | | | X | X | X | X | X |
| Recom. for A/C handling | X | | | | | | | | | X | | | X | | | | | | X | | |
| Recom. for repair quality | X | | | X | | | | | | X | | | X | | | | | | | X | |
| Recom. for MOS selection | | | | X | | | | | | | | | | | | | | | | | |
| Recom. for interoperability | | | | | X | | | | X | | | | | | | | | | | | X |
| No. of A/C considered | 1 | 1 +3 | 1 | (1) | (1) | 0 | 0 | 0 | 0 | 8 +2 | 0 | 2 | 1 | 0 | 1 | 0 | 0 | 1 | 3 | 1 +8 | |

TABLE 2 : RESULTS FROM TEST OF COMPUTATION

| " A/C Dynamic Response to Damaged and Repaired Runways " | Presented Papers | | | | | | | | | | | | | | | | | | | | RTD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | |
| | Col. | | | Ces. | | | - - - - Brussels - - - - | | | | | | | | | | | | | | |
| | | | | | | | overv. | | | | math. | | | | te. | | design | | | | |
| Test results; examples of : | | | | | | | | | | | | | | | | | | | | | |
| - influences of parameters | | | | | | | | | | | | | | | | | | | X | | |
| - probability distribution of parameter | | | | | | | | | X | | | | | | | | | | | | |
| Comparison: test - computation | X | X | | | | | | | | | | X | X | | X | | | X | X | | |
| Computation results; examples of: | | | | | | | | | | | | | | | | | | | | | |
| - influences of pertinent parameters | X | | X | | | | | | | | X | | X | | X | | | X | | X | |
| - negligible parameters | | | | | | | | | | | | X | | | | | | | | | |
| Profile data used in computations : | | | | | | | | | | | | | | | | | | | | | |
| - deterministic rough profile | | | | | | | | | | | | | | X | | | | X | | | |
| - single or multiple mat, bump, spall, ... | X | X | X | | | | | | | X | | | X | X | X | | | X | | X | |
| - spacing of repaired patches | X | | | | | | | | | X | | | X | | | | | | | X | |
| - random aspects | | | | | | | | | | | | | | X | | | | | | | |

TABLE 3 : PROBLEM AREAS AT A/C OR U/C

| " A/C Dynamic Response to Damaged and Repaired Runways " | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | RTD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Presented Papers | | | | | | | | | | | | | | | | | | | | |
| | Col. | | | Ces. | | | Brussels | | | | | | | | | | | | | | |
| | | | | | | | overv. | | | | math. | | | | te. | | design | | | | |
| Nose U/C loading | | X | X | | | | | | X | X | | X | | | X | | X | | X | X | |
| Main U/C loading | X | | | | | | | | X | X | | | | | | | | | X | X | |
| Shockabsorber bottoming | | | | | | | | | X | | | X | | | X | | X | | X | | |
| Tyre bottoming | X | | X | | | | | | | | | | | | | | X | | | X | |
| Wing loading - inner | | | | | | | | | | | | | | | | | X | | X | | |
| Wing loading - mid | | | | | | | | | | X | | X | | | | | | | | | |
| Wing loading - outer | | | | | | | | | | X | | | | | | | | | | | |
| Pylon loads | | X | | | | | | | | X | | | | | | | X | | X | | |
| Equipment loading | | | | | | | | | X | | | | | | | | X | | | | |
| Directional stability | | | | | | | | | X | | | | | | | | | | | | |
| Fuselage loading - forward | | | | | | | | | | X | | | | | | | | | | | |
| Fuselage loading - mid | | | | | | | | | | | | | | | | | | | | | |
| Fuselage loading - rear | | | | | | | | | | | | | | | | | | | | | |
| Cockpit acceleration | | X | | | | | | | X | | | X | | | | | | | | | |

TABLE 4 : PERTINENT PARAMETERS OF A/C AND OF EXTRANEOUS INFLUENCES

| " A/C Dynamic Response to Damaged and Repaired Runways " | Presented Papers | | | | | | | | | | | | | | | | | | | | RTD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | |
| | Col. | | | Ces. | | | Brussels | | | | | | | | | | | | | | |
| | | | | | | | overv. | | | | math. | | | | te. | | design | | | | |
| A/C rigid body modes | X | X | X | | | | | | | | | | X | | X | | | | | | |
| A/C elastic modes | | X | | | | | | | | | X | X | X | | | | | | X | | |
| A/C velocity; acc.; decel.; | X | | | | | | | | X | | | | X | | X | | | X | X | | |
| A/C aerodynamic (general) | X | X | | | | | | | X | | | X | | | | | | | X | | |
| A/C aerodynamic (spec.):grd.,thrust,prop. | | | | | | | | | | | | | X | | | | | | X | | |
| A/C handling: thrust, run up | | | | | | | | | | | | X | | | | | | | X | | |
| A/C handling: thrust, reverse | | | | | | | | | X | | | | | | | | X | | X | | |
| A/C handling: elevator operation | | | | | | | | | X | | | X | X | | | | | | X | | |
| A/C handling: brake operation | | | | | | | | | X | | | X | X | | | | X | | X | | |
| Wind | | | | | | | | | X | | | X | | | | | | | | | |
| Undamaged surface profile | | X | | | | | | | X | | | X | | X | X | | | | | | |
| Range of uncertainity of data | | | | | | | | | X | | | | | | | | | | X | | |

TABLE 5 : PERTINENT PARAMETERS OF U/C

| " A/C Dynamic Response to Damaged and Repaired Runways " | Presented Papers | | | | | | | | | | | | | | | | | | | | RTD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | |
| | Col. | | | Ces. | | | Brussels | | | | | | | | | | | | | | |
| | | | | | | | overv. | | | | math. | | | | te. | | design | | | | |
| U/C location (turn over angle) | | | | | | | | | | | | | | | | | | | | X | |
| U/C main + nose mass coupling | | | | | | | | | | | | | | | | | | | | | |
| U/C main + nose spring coupling | | X | | | | | | | | | | | | | | | | | | | |
| U/C kinematics | | | | | | | | | | | X | | | | | | | | | X | |
| U/C elasticity | | | | | | | | | | | X | | | | X | | | | | | |
| U/C active control | | | | | | | | | | | | | | | | | | | | | |
| Shock absorber : stroke | X | X | | | | | | | | | | | | | X | | | | X | X | |
| Shock absorber : limit loads | | | | | | | | | | | | | | | | | X | | X | | |
| Shock absorber : airspring stiffness | X | X | | | | | | | X | | | | | | | | | X | | X | |
| Shock absorber : damping general | | | X | | | | | | X | | X | | | | | | | | | | |
| Shock absorber : damping compression | | | | | | | | | | | | | | | | | | X | | X | |
| Shock absorber : damping recoil | | | X | | | | | | | | | | | | | | | | | | |
| Shock absorber : friction | | | | | | | | | X | | X | | | | | | | | | X | |
| Shock absorber : overload valve | | | | | | | | | | | | | | | | | | | | X | |
| Wheel (mass, size, No.) | | | | | | | | | | | X | | | | | | | | | X | |
| Tyre (size, pressure, stat.deflect.) | | X | | | | | | | X | | | | | | | | | | X | X | |

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**14. Abstract**

The conclusions of the Meeting were: damaged and repaired runways are likely to be very uneven and possibly dangerous to aircraft operations; there is very little realistic data on the expected amount and extent of the unevenness. With respect to existing NATO aircraft; each aircraft/runway combination must be checked analytically and experimentally; the existing mathematical models for dynamic response of aircraft structures and landing gear are reasonably accurate; some simple modifications to aircraft equipment and pilot technique show substantial improvements in dynamic response. For future aircraft or modifications to the current fleet, there is a need for a NATO-wide "groundworthiness" requirement to allow true *interoperability* of NATO's air forces.

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